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**AEROELASTIC STABILITY TESTS OF
THIN CYLINDRICAL SHELLS AT
SUPERSONIC SPEEDS
(FOLLOW-ON TESTS)**

Warren E. White

ARO, Inc.

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FOREWORD

The work reported herein was done at the request of the Aerospace Engineering Department of the University of Texas for the Air Force Office of Scientific Research (AFOSR), Air Force Systems Command (AFSC), under Program Element 61102F, Project 9782.

The results of the test presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract F40600-69-0001. The test was conducted from January 7 through 20, 1969, under ARO Project No. PS0931. The manuscript was submitted for publication on April 2, 1969.

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This technical report has been reviewed and is approved.

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ABSTRACT

Follow-on tests to an investigation to determine the dynamic characteristics of thin cylindrical shells were conducted in the Propulsion Wind Tunnel, Supersonic (16S). The model consisted of an ogive cylinder with the test shell located on the cylindrical portion of the model approximately 78 percent of the model length aft of the nose. Data were recorded at Mach numbers of 2.2 and 2.5 for 0-deg angle of attack and yaw. Flutter was induced on the 0.0020- and 0.0032-in. - thick shells by reducing the model cavity pressure. Boundary-layer measurements were also made at various boundary-layer blowing rates.

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NOMENCLATURE

D	Model reference diameter, 1.333 ft
E	Young's modulus of elasticity, 2.736×10^9 , psf
\bar{F}	Flutter parameter, $\left(\frac{q_\infty}{E \sqrt{M_\infty^2 - 1}} \right)^{1/3} \frac{R}{h}$
h	Shell thickness, in.
L	Shell reference length, 1.333 ft
M_L	Local Mach number
M_∞	Free-stream Mach number
p	Pressure measured on the model surface downstream of the test shell, psi
p_c	Cavity pressure beneath the shell, psi
$p_{t\infty}$	Free-stream total pressure, psf
q_∞	Free-stream dynamic pressure, psf
R	Shell radius, 8.00 in.
Re/ft	Reynolds number per foot, $\frac{V_\infty}{\nu_\infty}$
V_∞	Free-stream velocity, ft/sec
\dot{w}	Weight flow into boundary layer, lb/sec
x	Distance from the forward edge of the test shell, ft
y	Distance measured normal to the model surface, in.
Δp_c	Differential pressure across the shell, $(p_c - p)$, psi
ν_∞	Free-stream kinematic viscosity, ft^2/sec
ϕ	Rotational angle measured on the model (Fig. 4), deg

SECTION I

INTRODUCTION

The follow-on tests to the cylindrical shell flutter program reported herein were done at the request of the Aerospace Engineering Department of the University of Texas, Austin, Texas. The test was conducted on an ogive cylinder model in the Propulsion Wind Tunnel, Supersonic (16S) at 0-deg angle of attack and at Mach numbers of 2.2 and 2.5. The purpose of the test was to determine the effects of boundary-layer characteristics with controlled boundary-layer blowing on the dynamic behavior of the shell.

The related tests are covered in Refs. 1 and 2 which present static pressure distributions, boundary-layer profiles, and shell flutter data for Mach numbers from 1.20 to 3.0.

SECTION II

APPARATUS

2.1 WIND TUNNEL

Tunnel 16S is a variable density wind tunnel capable of operating at Mach numbers from 1.5 to 4.75. The test section is 16 ft square and is composed of two 20-ft-long removable sections. A more complete description of the tunnel may be found in Ref. 3, and calibration results are presented in Ref. 4. A sketch of the model installed in the test section is presented in Fig. 1, and a photograph of the model is presented in Fig. 2.

2.2 TEST ARTICLE

The geometry of the cylindrical shell model is presented in Figs. 3 and 4. Additional shells of thicknesses from 0.002 to 0.004 in. were supplied, and an auxiliary boundary-layer bleed was incorporated in the model since the previous tests. The auxiliary bleed was incorporated near the end of this test and consisted of 0.063-in. holes 0.5 in. apart drilled into the axial bladder and directed toward the surface 90 deg to the airstream. This permitted a diffusive blowing into the boundary layer immediately upstream of the test shell.

The test shell itself was a right-circular cylinder 16 in. in diameter and 16 in. long and began 96 in. aft of the model nose and 48 in. aft of

the beginning of the cylindrical portion of the model. The thicknesses of the shells were 0.0020, 0.0032, and 0.0040 in. The pressure differential across the shell was controlled by varying the internal pressure. High-pressure rubber bladders were used to seal the internal cavity and prevent pressure loss. Axial loading on the shell could be applied by inflating a bladder which acted on the forward-end ring of the shell. This bladder was later used for the auxiliary boundary-layer bleed. A more detailed description of the model may be found in Ref. 2.

Three rakes were used to measure the boundary-layer profiles. Rake 1 was adjustable in height and mounted at $\phi = 33$ deg; whereas, rake 2 was fixed and mounted at 147 deg. Rakes 1 and 2 were located 0.5 in. forward of the aft edge of the shell. Rake 3 was used to investigate the boundary-layer growth from the blowing slot and auxiliary blowing position to the aft portion of the test shell by traversing the distance in finite steps.

SECTION III TEST DESCRIPTION

3.1 TEST PROCEDURE

The test was conducted at Mach numbers of 2.2 and 2.5 for angles of attack and yaw of 0 deg. Dynamic data were tape recorded continuously; whereas, the steady-state data were acquired during boundary-layer study and pauses during flutter and buckling search. A summary of the flutter results is given below in Table I. Flutter and buckling characteristics were obtained at a Mach number of 2.2 only. Test conditions were established initially at a low dynamic pressure. The dynamic pressure was then slowly increased until a designated increment was reached, at which time internal pressure and shell axial loading were varied to induce flutter or buckling.

TABLE I
SUMMARY OF TEST INFORMATION

M_∞	p_{t_∞} , psf	q_∞ , psf	$Re/ft, \times 10^{-6}$	\bar{F}	Δp_c , psi	h , in.	\dot{w} , lb/sec	Remarks
2.2	988	313	1.465	10.7	0.64	0.0032	0	Zero axial loading
2.2	350	111	0.543	12.1	0.24	0.0020	0	Zero axial loading

Boundary-layer profile data were obtained from the three rakes at several boundary-layer blowing rates and at several tunnel pressures.

3.2 INSTRUMENTATION

Twenty-nine total pressures were measured from the three boundary-layer rakes (Figs. 5 and 6), and a static reference pressure was measured on the model surface. Pressure measurements inside the sealing (radial) bladders and the loading (axial) bladder were recorded, as were pressures within the boundary-layer blowing system and the model cavity region.

Three mutual inductance proximity sensors were used to monitor the static and dynamic displacement of the shells. The sensors operated without contacting the shell surface with maximum output of approximately 4 v occurring when the shell surface was far away. The output decreased as the metal skin neared the sensor head. One of the three sensors could be positioned longitudinally and circumferentially, a second could be positioned longitudinally only, and the third was fixed. The signals from the sensors were recorded on magnetic tape.

Instrumentation was not available for weight flow determination of the auxiliary boundary-layer blowing system; however, approximate values were calculated by assuming choked flow at the axial bladder orifices and a nominal temperature of 110°F. A pressure regulator was used in setting and monitoring auxiliary flow rate.

A more complete description of the instrumentation may be found in Ref. 2.

3.3 PRECISION OF MEASUREMENTS

The uncertainties in setting and maintaining tunnel conditions are as follows:

Mach number	± 0.005
Total pressure	± 5 psf
Total temperature	$\pm 5^\circ\text{F}$
Angle of attack	± 0.1 deg

The longitudinal variation of Mach number along the tunnel center-line has a maximum value of ± 0.02 .

The uncertainties associated with the tunnel pressure measuring system yield uncertainties in the pressure-coefficient data as follows:

M_∞	$Re/ft \times 10^{-6}$	ΔC_p
2.2	0.290	0.0110
2.2	1.730	0.0026
2.5	0.342	0.0112
2.5	2.342	0.0020

SECTION IV RESULTS AND DISCUSSION

Mach number boundary-layer profiles were obtained during the auxiliary boundary-layer blowing and are presented in Figs. 7 and 8. Data from all three rakes with the longitudinal position 0.5 in. forward of the aft edge of the shell are presented in Fig. 7. The auxiliary boundary-layer weight flow was varied from 0 to 0.30 lb/sec. The boundary layer appeared to be turbulent for $\dot{w} \geq 0.18$ lb/sec at $p_{t_\infty} = 325$ psf and for $\dot{w} \geq 0$ for $p_{t_\infty} = 400$ psf. Figure 8 is a comparison of boundary-layer profiles at various axial positions with and without auxiliary boundary-layer blowing. Laminar flow existed at all model locations for zero blowing rate. A turbulent boundary layer becomes noticeable at $x/L \geq 0.55$ for weight flow of 0.30 lb/sec. Boundary-layer data obtained using the previously existing blowing slot were indicative of results reported in Ref. 2 and are therefore not presented.

A summary of flutter conditions is presented in Table I. At total pressures of 350 and 988 psf, flutter was induced for the 0.0020- and 0.0032-in. -thick shells, respectively, by reducing the model cavity pressure at zero axial loading. On one 0.0020-in. shell, flutter conditions, reported in Ref. 2, of $p_{t_\infty} = 300$ to 510 psf, $\bar{F} = 13.0$ to 25.9, and $\Delta p_c = 0.75$ to 3.6 were duplicated in an attempt to repeat flutter. Search for flutter was unsuccessful between total pressures of 300 to 400 psf. The shell was accidentally buckled as p_{t_∞} was being increased from 400 psf. Cavity pressure and Δp_c were zero at the time of buckling.

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3. Test Facilities Handbook (Seventh Edition). "Propulsion Wind Tunnel Facility, Vol. 5." Arnold Engineering Development Center, July 1968.
4. Parli, C. L. and Sloan, E. H. "Aerodynamic Calibration of the AEDC 16-Foot Supersonic Tunnel Compressor with Fiber Glass First Cylinder Rotor Blades." AEDC-TR-69-79, to be published.

**APPENDIX
ILLUSTRATIONS**

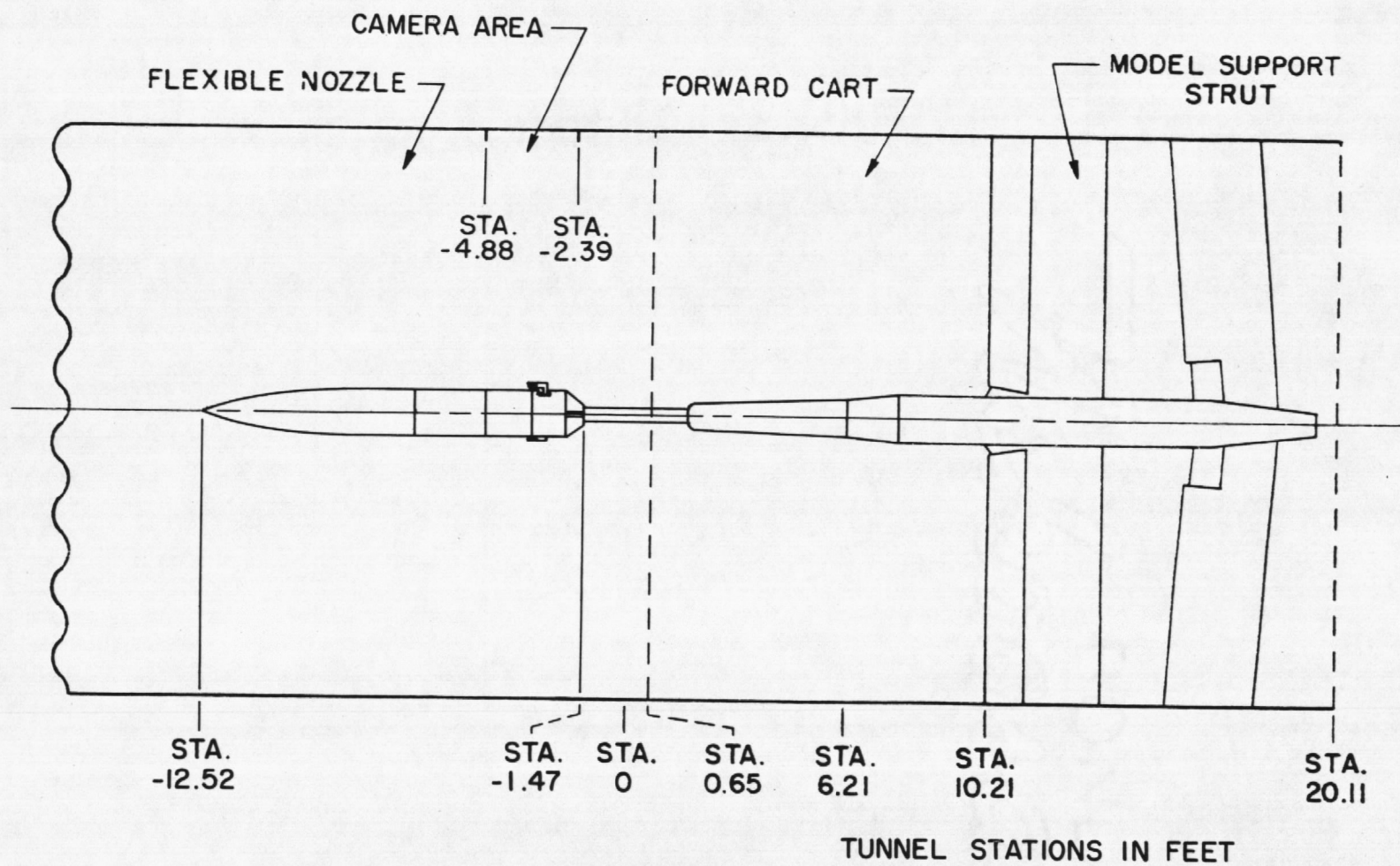


Fig. 1 Sketch of the Model in the Tunnel 16S Test Section

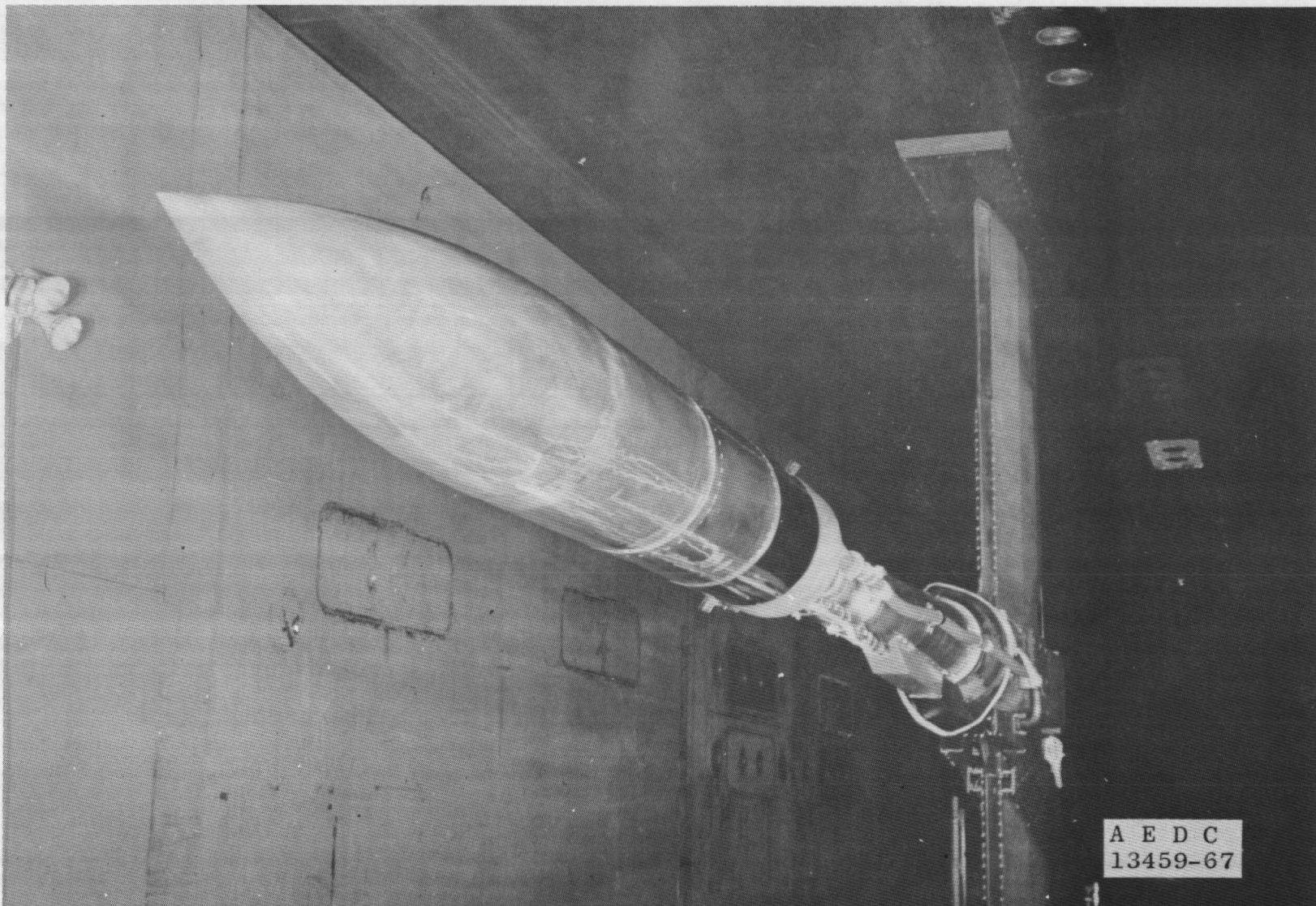


Fig. 2 Photograph of the Model Installed in the Tunnel 16S Test Section

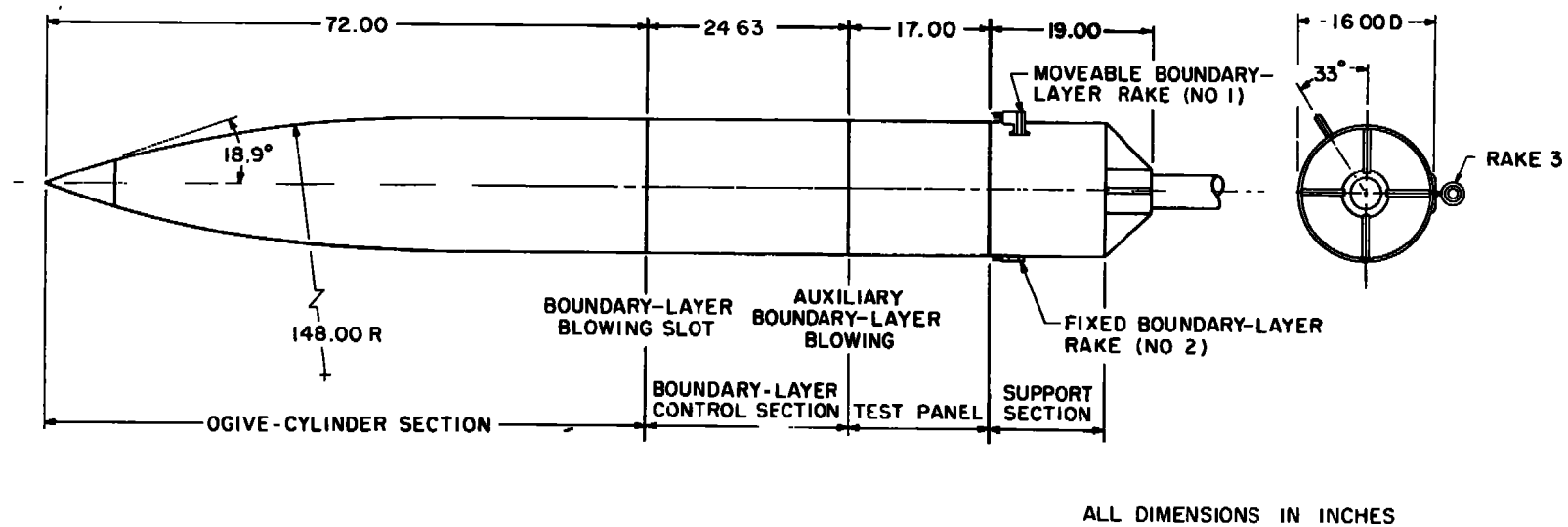


Fig. 3 Model Dimensions and Details

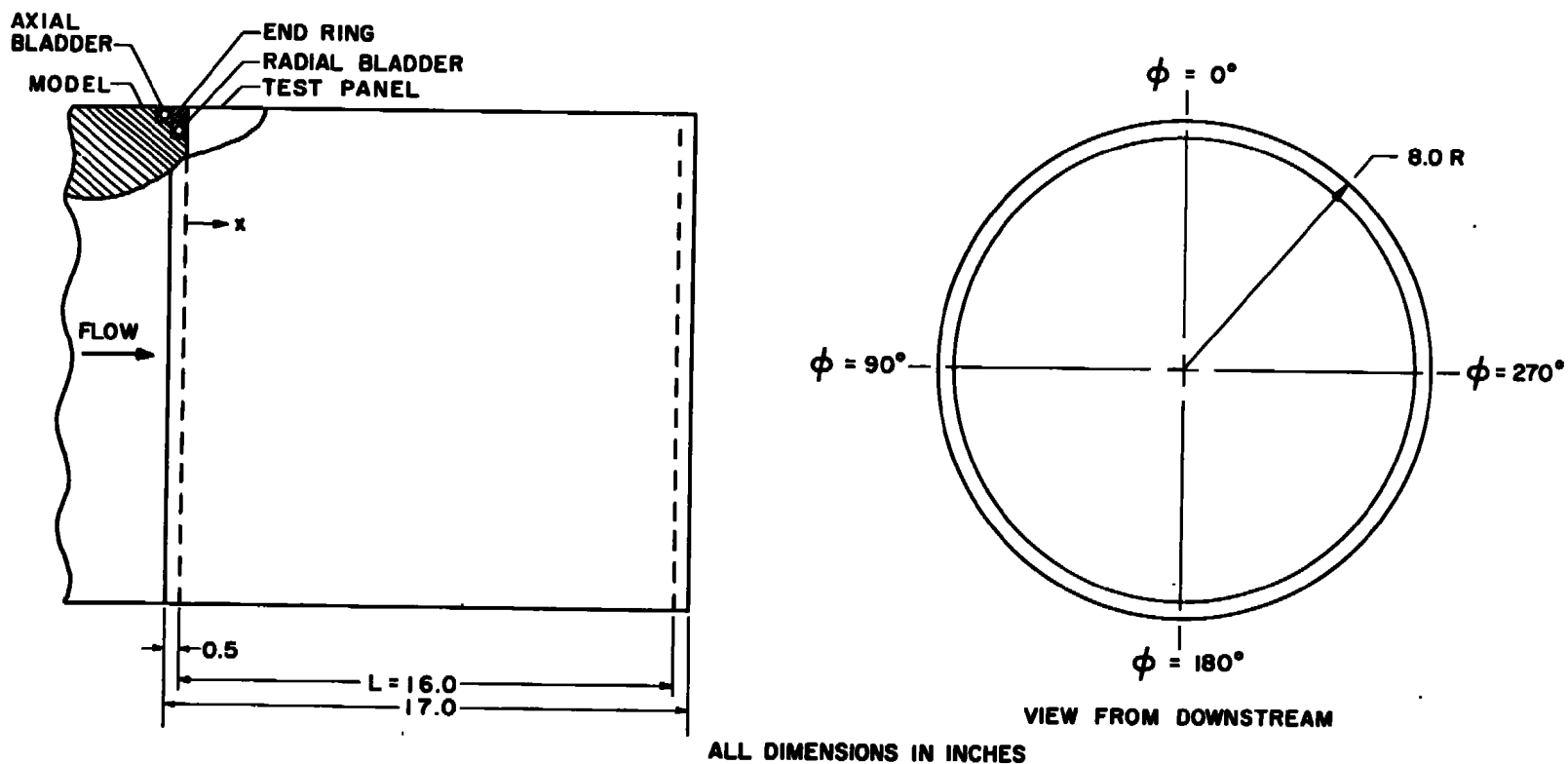


Fig. 4 Details of the Test Panel

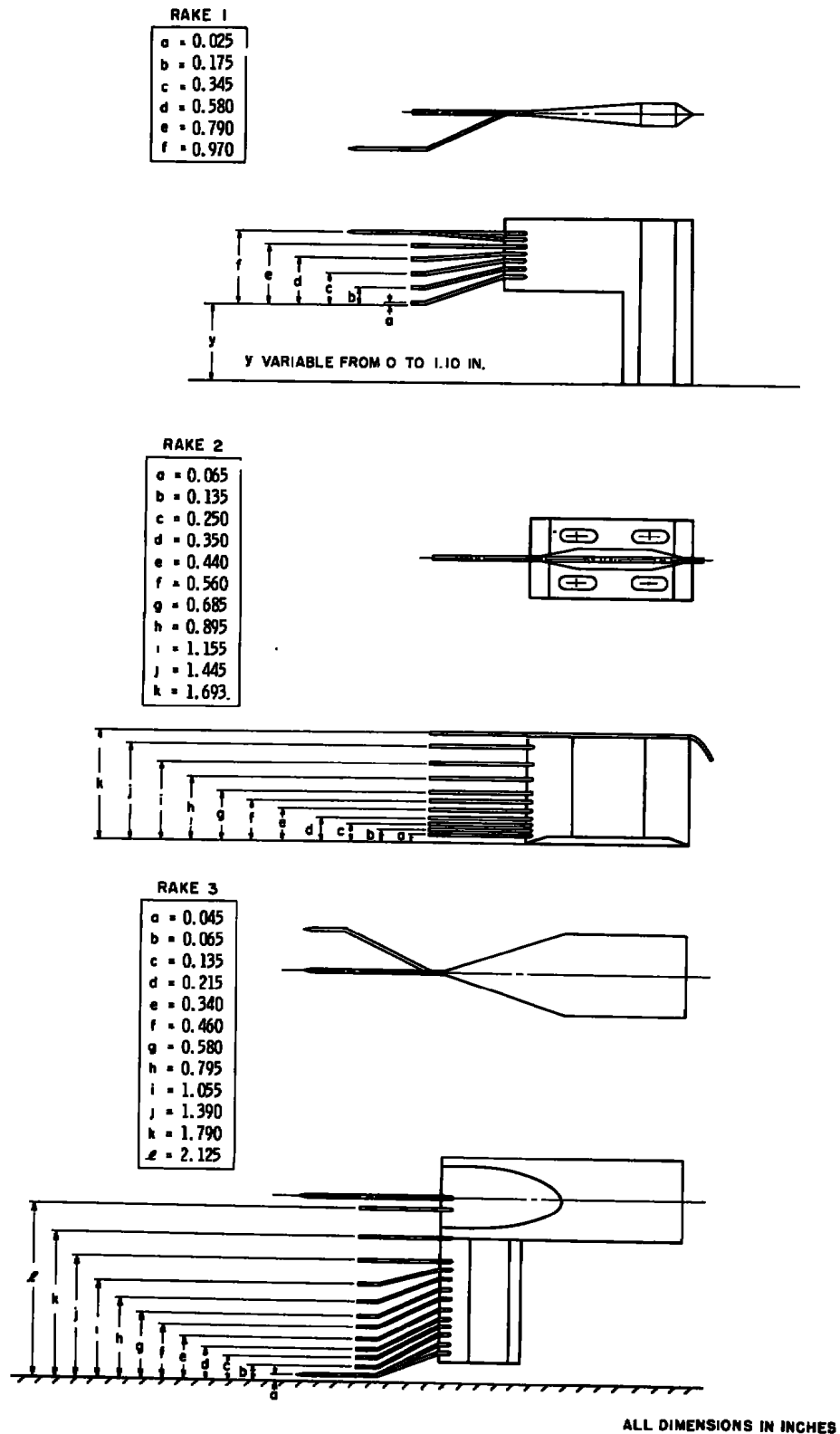
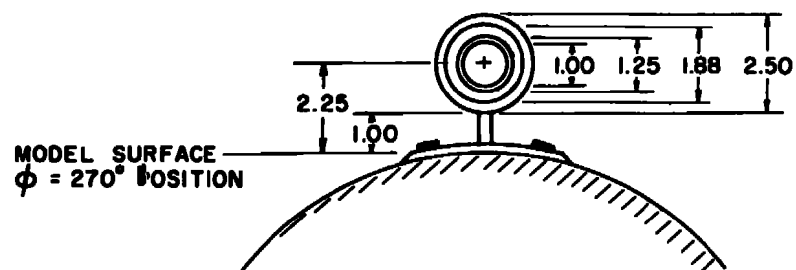
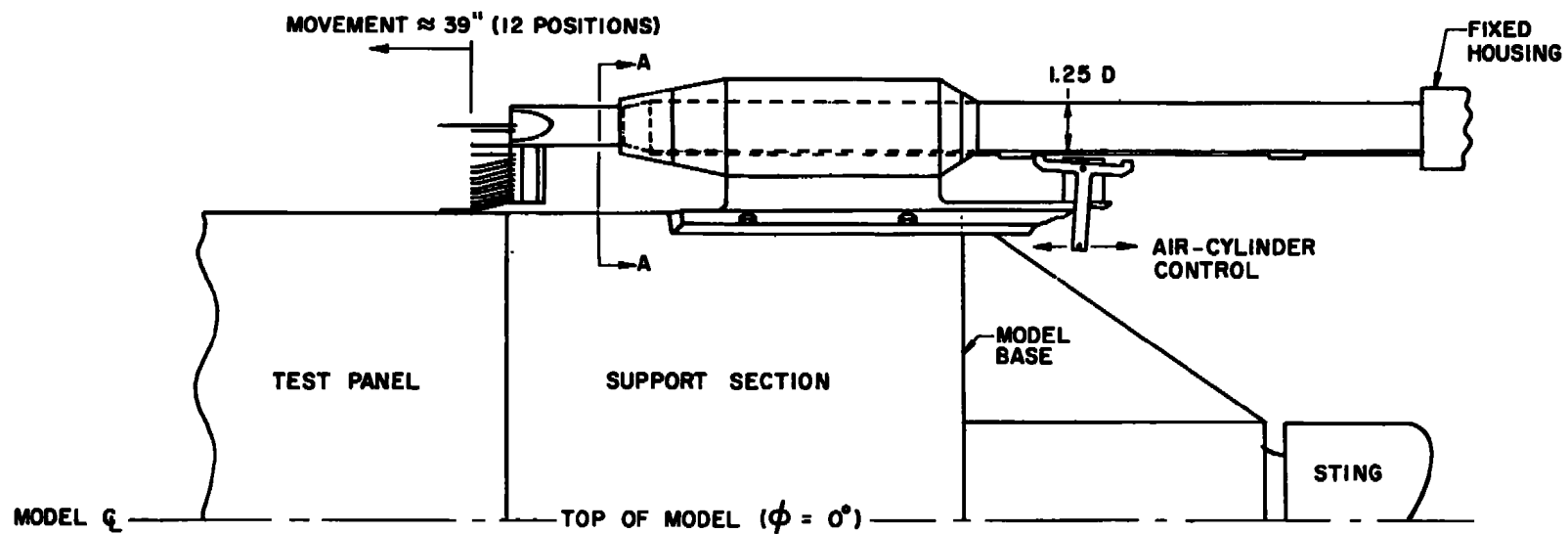


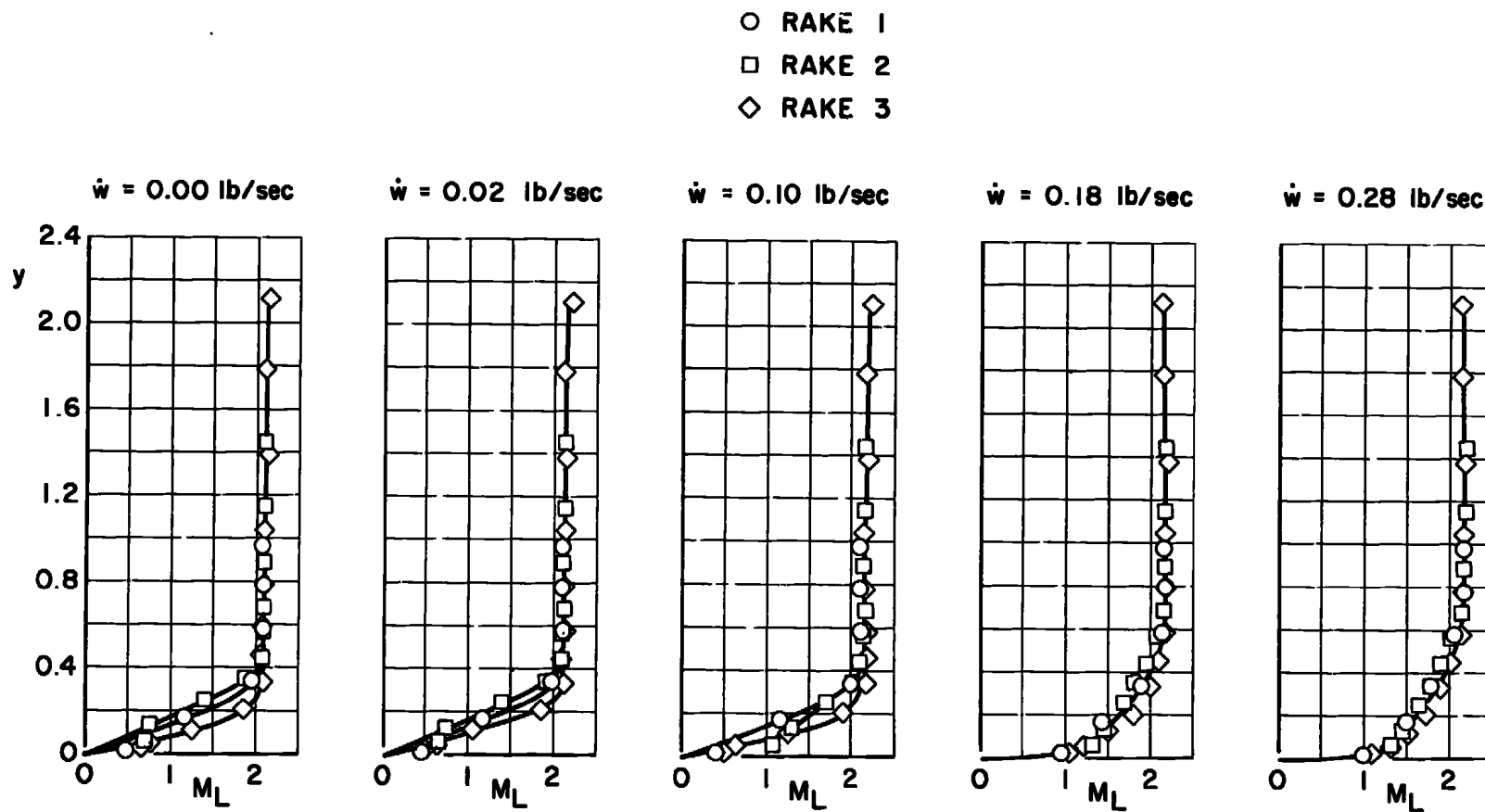
Fig. 5 Details of the Boundary-Layer Rakes



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SECTION A - A

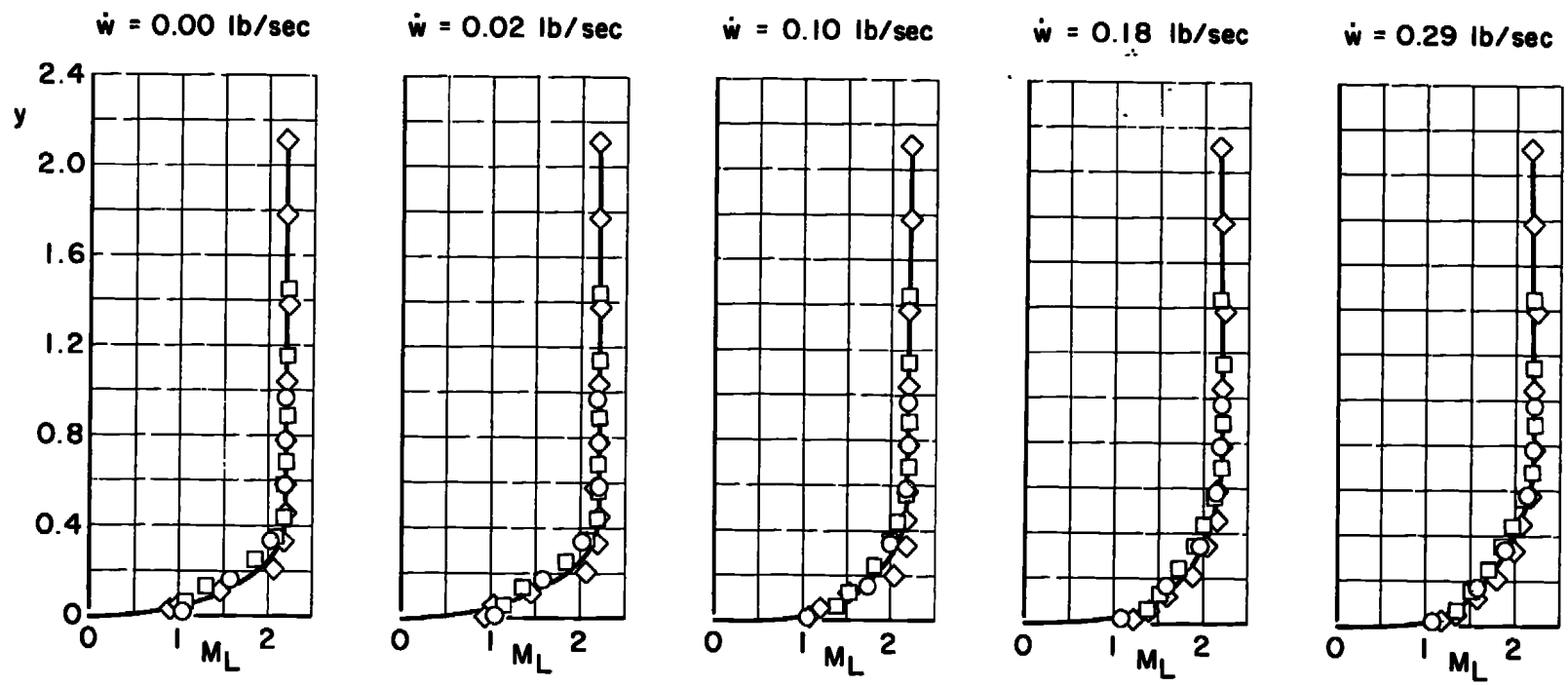
Fig. 6 Sketch of the Traversing Rake (Rake 3)



a. $p_{t\infty} = 325 \text{ psf}$, $Re/ft = 0.496 \times 10^6$

Fig. 7 Local Mach Number Profiles as a Function of Auxiliary Boundary-Layer Weight Flow, \dot{w} , at $x/L = 0.97$, $M_\infty = 2.2$

- RAKE 1
- RAKE 2
- ◇ RAKE 3



b. $p_{t\infty} = 400$ psf, $Re/ft = 0.598 \times 10^6$
 Fig. 7 Concluded

○ ZERO WEIGHT FLOW
 □ APPROX. 0.30 lb/sec WEIGHT FLOW

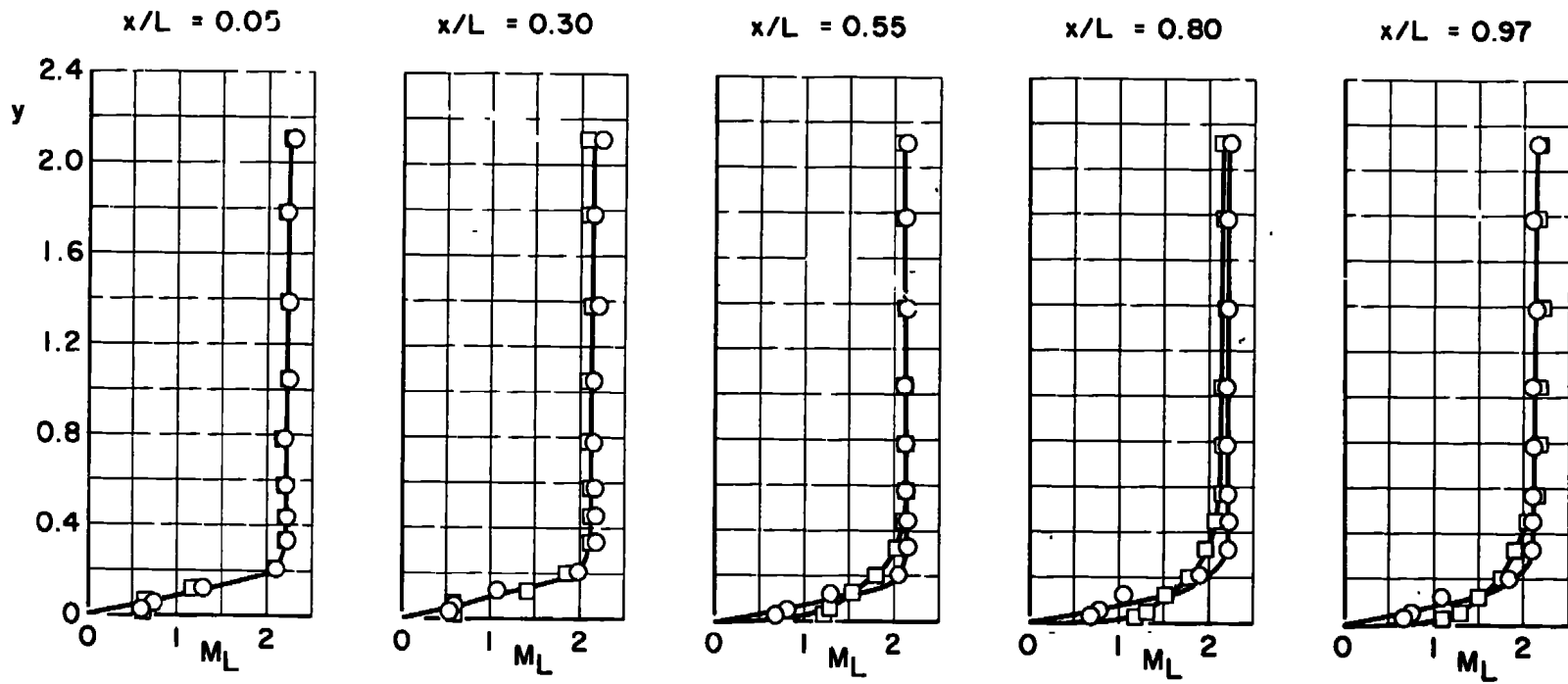


Fig. 8 Local Mach Number Profiles with and without Auxiliary Boundary-Layer Weight Flow, w , at Shell Stations x/L from 1 to 0.97, $M_\infty = 2.2$, $p_{t\infty} = 400$ psf, $Re/ft = 0.598 \times 10^6$

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1. Shells --- 7 flutter

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Supersonic flow

Aeroelastic stability

1-2